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WAKE VORTEX DISPLAY DESIGN AND MODEL EVALUATION

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In a Phase I Small Business Innovative Research (SBIR) project for NASA Langley, we developed and evaluated three formats of conceptual prototype cockpit wake vortex displays, a 2D plan view display, a 2D co-planar display, and a 3D synthetic vision system display. In each, the wake was presented along with conventional information on the 2D nav display, the vertical situation display, and the forward-looking SVS display. In the first stage of evaluation, three pilots carried out a two rounds of usability analyses on the displays in dynamic flight scenarios. The co-planar display was revealed to have the fewest problems. In the second stage, we evaluated the three displays, and some variants using a dynamic computational model of attention-situation awareness (A-SA), to reveal that the SVS display with wake information redundantly presented on a coplanar display yielded highest situation awareness and shortest noticing time for the appearance of the wake. The 2D nav display was poorest.

Introduction

The wake vortex represents an emerging threat in aviation, both as increasing numbers of larger transport aircraft are flying and, looking to the future, as plans are made to address the capacity problems of an increasing dense airspace by spacing aircraft closer together on approach and departure. The wake vortex (WV) is a hazardous entity emanating from the wings of a leading aircraft which, if encountered by a smaller trailing aircraft, can impose severe turbulence. Aircraft spacing on approach and departure is typically very large, to assure that such encounters never happen. Such large spacing reduces the capacity of departure and arrival routes. With WV displays in a cockpit, pilots can better adjust their longitudinal separation, to be closer (thereby increasing flight path capacity), but not so close as to encounter the wake, which itself follows a complex 4D time-space trajectory as it dissipates. In order to provide pilots with a spatial sense of wakes generated by aircraft ahead, it is necessary to have an accurate model of wake propagation (Holferty and Powell, 2001), coupled with an intuitive display of the wake behavior in the cockpit.

The wake vortex is typically a somewhat rectangular area of turbulence that sinks behind the generating aircraft, dissipating in strength, as time passes from its generation at each point along its extent. It may be effected by cross winds. Its initial strength will be proportional to the size of the generating aircraft, and its disruption of the trailing aircraft will be greater for smaller trailing aircraft. In the following pages we

describe two phases of our project: a user-centered design of three display prototypes, and a model-based evaluation of each.

User Centered Design.

Based on input from subject-matter experts, and consideration of lessons learned from other cockpit-based hazard displays (in particular traffic and terrain warning systems; Thomas & Wickens, 2006; Alexander Merwin and Wickens, 2004), we developed three different versions of a wake vortex alerting display:

- a 2D plan view display, which could be readily incorporated within the traditional navigational Horizontal Situation Display (HSD).
- A co-planar view, including a vertical situation display (VSD) augmenting the HSD. The VSD being introduced on advanced aircraft could readily accommodate this vertical view of the wake.
- A 3D forward looking view, which could be incorporated within the framework of a synthetic vision system (SVS) display (Prinzel et al, 2004; Alexander Wickens and Hardy, 2005).

These three display formats are shown in figure 1.

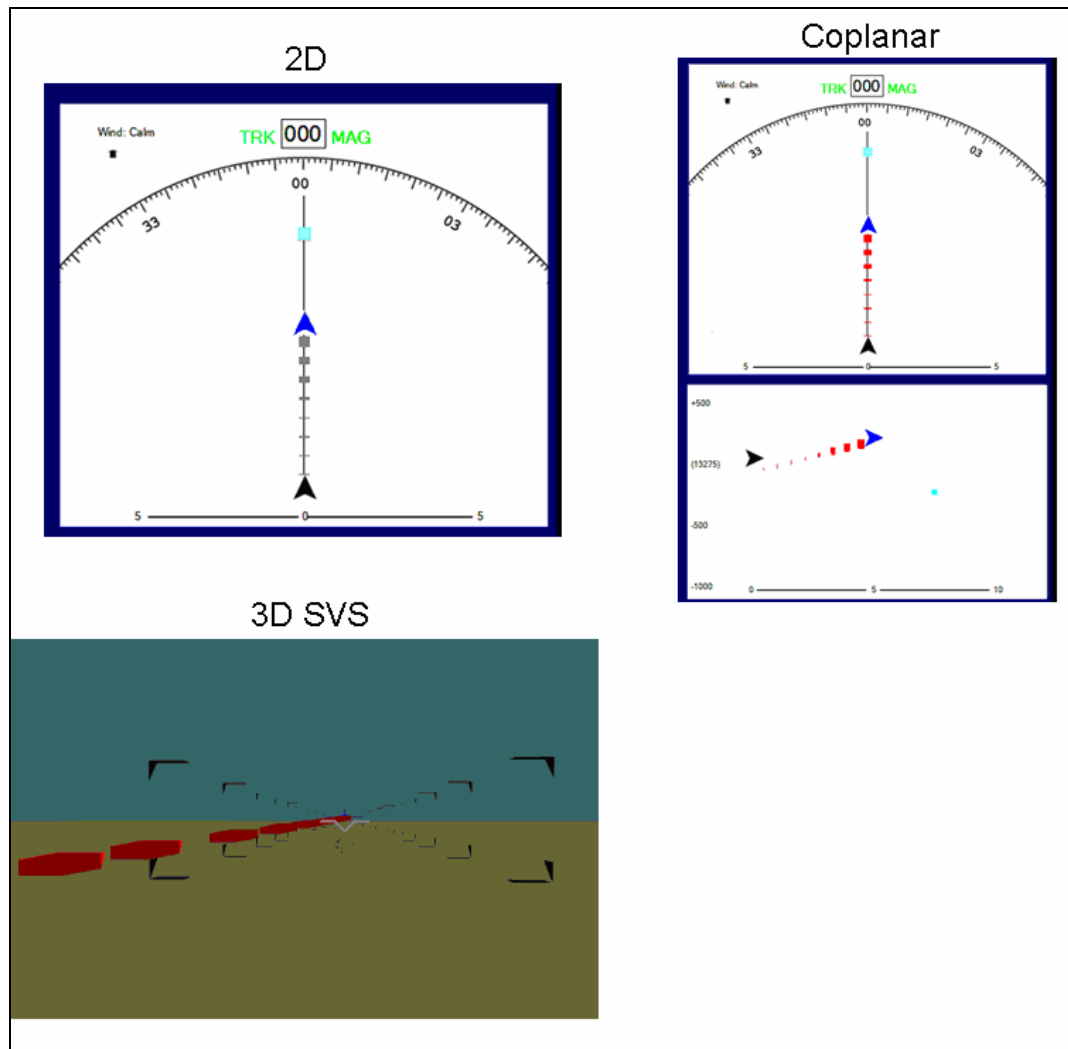


Figure 1. The three display formats. Ownship is at the bottom (or left) of the display. The WV can be seen diminishing in intensity and decreasing in altitude on the vertical situation display (VSD) component of the coplanar display

An important component of each display was the philosophy of wake representation, modeling a 4D trajectory, and rendering this trajectory in terms of two components:

- diminishing intensity and altitude as a function of the time since wake generation.
- Threat to ownship as a function of the projected **time until**, or **likelihood of** contact with the wake element. Threat was partitioned into three levels, generating *red wake symbols* when contact with an above-threshold wake intensity was likely, *grey wake symbols* (low contrast) when such contact was unlikely on the current trajectory, but could become probable if the trajectory was altered, and *no wake symbols* otherwise (although the generating traffic symbol remained visible).

The three display formats were given heuristic evaluations by three subject matter experts (high time pilots). Each, surprisingly, showed preference for a different format; all had useful comments for improving each format. Following an initial evaluation, we re-designed each format on the basis of the integrated recommendations, and then provided two of these for a subsequent evaluation, in which the different displays were visualized as intruder aircraft flew a series of different geometries during own-ship climb and descent profiles (e.g., overtaking, crossing, following, with and without cross winds). (The 3D SVS display was excluded from this analysis because of programming difficulties in implementing the dynamic 3D display)

Pilot comments on these scenarios in turn led to the final design of the three, as shown in figure 1. It should

also be noted that the overall most-favored format was the co-planar display. This reflected the fact that, given the vertical behavior of the wake, pilots felt it important to represent this on an analog vertical scale (the VSD), thereby rejecting the 2D display. However given the need to appreciate wake behavior across a wide range of space, pilots were uncomfortable with the forward looking SVS display format. In particular, this might leave the wake generated from an overtaking or crossing aircraft at a higher altitude undepicted until it generated a major threat. Further, the SVS display provided an imprecise representation of wake location because of 3D ambiguity (Wickens, 2003), which pilots perceived as a shortcoming of that display type. Pilots felt a desire to have a preview of such wakes well before they became threats. Thus in our formal evaluation of the three formats, we did not include an SVS only display, but rather one in which the forward looking SVS contained the wake, and was coupled with a wake representation on the VSD and HSD.

Formal Model Evaluation.

Our work included a second type of evaluation using a computational model of pilot performance to predict display effectiveness. We used the Attention-situation awareness (A-SA) computational pilot performance model, developed with support from NASA Ames research center, which has also been applied to synthetic vision system display evaluation (Wickens et al, 2007). The model generates predictions of the situation awareness supported by the different display formats. The model contains two modules:

(1). An **attention module**, characterizing stage 1 situation awareness, guides vision to sample different areas of interest, hence mimicking visual scanning (Wickens et al, 2003, 2006). It is assumed that sampled areas will be noticed or perceived. Four variables influence the direction of attention: the **salience** of events occurring within a display, the **effort** required to move attention to different locations (more effort inhibits attention movement), the **expectancy** for events and changes within a given display (expectancy is closely related to the bandwidth of the areas depicted), and the **value** of noticing, or cost of failing to notice, events within those displays. The four first letters of these factors define the **SEEV model** of selective attention.

(2). A **situation awareness module**, which actually characterizes level 2 SA (understanding). When any display containing wake information is sampled (as predicted by the SEEV attention module), it is modeled to discretely increase SA (in this case “wake awareness”) to a near maximum value. However

additional factors can diminish SA from this value. The passage of time causes an exponential decay of SA which is more rapid when other tasks compete for attention. In addition to the decay, other properties, like an ambiguous representation of the wake, drive SA below its maximum value (see Sebok et al, 2006).

Thus the two modules of the A-SA model can work in tandem, driving scanning across the various displays and areas of interest (AOI) shown in figure 2, and using the visual sampling of wake-hosting areas to temporarily boost SA, subject to decline when the scan moves somewhere else (e.g., to support flight control).

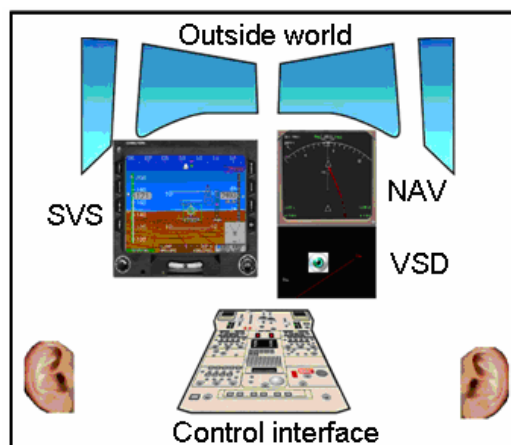


Figure 2. Schematic representation of the cockpit layout over which the eye moved during scanning. Within the primary flight display to the left, separate attention areas were designated for the wake symbol, and for the attitude information. The ears are represented as a destination of attention for aural alerts.

The model predicts the pattern of visual attention allocation across dynamic displays, as a function of their bandwidth, importance, display layout separation and event salience, and from this attention allocation vector it generates:

- an estimate of the time to notice discrete events on the display (e.g., an appearance of the wake symbol...level 1 situation awareness)
- an estimate of the level of understanding of wake behavior (levels 2 and 3 situation awareness).

This model, which has also been applied to synthetic vision system display evaluation (Wickens et al, 2007), was applied to a variety of wake scenarios, across the following nine conditions:

1. HSD 2D Display only
2. Coplanar display (i.e., wake on both HSD and VSD)
3. 3D SVS with wake only on SVS
4. 3D SVS with wake redundantly on coplanar HSD and VSD
5. Coplanar with aural alert (model run only to assess transition or noticing time).
6. Coplanar, pilot engaged in vertical maneuvering (constant heading)
7. HSD-only, pilot engaged in vertical maneuvering (constant heading)
8. Coplanar, pilot engaged in lateral maneuvering (constant altitude).
9. HSD-only, pilot engaged in lateral maneuvering (constant altitude).

In coding the parameter values for the model we followed standard A-SA procedures (see Wickens et al, 2007; Sebok et al, 2006), but made the following critical assumptions: (1) the onset of a visual wake representation had a salience value of 1, and the aural alert had a salience value of 2, characterizing the greater attention capturing properties of sound. (2). Effort to scan between adjacent displays was less than that to scan between displays separated by one or more. (3). The primary flight display contained higher bandwidth (higher expectancy) changes than did the Nav display. (4) Aviating (supported by the primary flight display) was more valuable than navigating. (5). When different aspects of the wake were supported by two displays (e.g, in the co-planar format), there was an SA penalty for imbalanced scanning, or neglect of one or the other of these panels.

Results

Because the SEEV model captures the statistical variability of scanning behavior, it was run multiple times (equivalent to an experiment carried out with multiple replications) to provide mean measures of SA (averaged across a phase of flight), and of noticing time. While full results are presented in Sebok et al, the following are a summary of key observations that were made.

1. The model generated the following order of displays, from best to poorest, in terms of the SA wake awareness value (shown in parentheses below) during the post-wake period:
 - o SVS redundant wake on coplanar (0.76),
 - o Coplanar (0.67),
 - o SVS only (0.63),
 - o HSD-only (0.36).
2. In terms of the second important aspect of wake awareness: noticing time in seconds, the

following order (from fastest to slowest) corresponds precisely to that obtained for overall wake awareness. This listing also contains the aural alert, which was not computed for the SA measure.

- o SVS redundant (1.84 s),
- o Coplanar (2.0 s),
- o Aural only (2.35 s),
- o SVS only (2.65 s),
- o HSD-only (3.8 s).

In considering these overall figure of merit ratings, in the context of the scanning measures that generated them, a few observations are noteworthy:

1. Any format coupled with the co-planar display performs better than without it. This is because, in normal scanning, both the VSD and HSD panels of the Nav Display command a good deal of visual attention, supporting general navigational functioning (26% to 31% of fixation time) and this attention will (a) support wake awareness after the wake is noticed, and (b) make it more likely that the wake will be noticed because the eye is positioned on these displays when the wake appears.
2. The absence of the VSD causes a clear drop in both wake awareness and the speed of noticing.
3. For the SVS-only display format, the benefit of having the wake symbol close to the frequently fixated primary flight display, is offset by the cost of not having this symbol redundantly represented on the two components (HSD and VSD) of the Nav display, both for noticing and for subsequent SA.
4. The fact that the aural display (in which the wake onset is not represented visually on the other displays) shows a longer noticing time than the two formats in which the wake is represented on the Coplanar Nav display components (HSD and VSD), reflects the great value added of having these often-attended visual components present, a value which more than offsets the greater salience of the auditory alert.
5. Importantly, the model provided data on the numerical relative costs or benefits of different formats, not simply “which is better”. This will allow designers to make tradeoffs of situation awareness support, against other key variables (workload, cost, etc.)

Conclusion

In conclusion, two evaluations have revealed that the optimal format for a wake vortex display includes redundant presentation between a 3D SVS display, and a nav display that has both horizontal (HSD) and vertical (VSD) components. If an SVS suite is not present, then it becomes very important to present vertical wake information on a VSD. The current evaluation did not examine pilot-in-the loop simulation, using the model instead to emulate the results of such a simulation. Given both the validity of the model established elsewhere (Wickens et al, 2007), as well as the sense that the conclusions from model evaluations coincided with conclusions from other pilot-in-the loop studies on 3D and 3D hazard displays (e.g., Thomas & Wickens, 2006; Wickens, 2003; Alexander Wickens and Merwin, 2004), we have relative confidence in the current results; but argue strongly that such experimentation take place.

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